1. MILKY WAY

Only in 20th century it was understood that the Sun is inside Milky Way (MW) and many galaxies like MW are outside (see **Great Debate** in the year 1920). Stars, gas & dust in MW understood only in last 2 decades. Sun 8.5 kpc from center, rotates around center at velocity **$v \approx 220$ km/s, 1 loop in 2.4×10^8 yr** (typical for stars in the disk).

Baryonic mass:	$M_b = 10^{11}\ M_\odot$	
Number of stars:	$(3 \pm 1) \times 10^{11}$	
Gas	$M_g = 10^{10}\ M_\odot$	
Dust	$M_d = 10^9\ M_\odot$	
Total mass:	$M_T = 10^{12}\ M_\odot$	(mainly non baryonic)
Age:	$12\text{-}14 \times 10^9$ yr	

Mass dominated by dark matter (DM) which is 90% of the total. Size depends on what component considered. Stellar disk: 100,000 l.y. (~ 30 kpc). Disk 1 kpc thick. Size of gas disk (low density neutral hydrogen HI) is 50 kpc across.

Dark matter (DM, mostly non baryonic) dominant, mass in stars (10%) gas (1%) dust (0.1%) of DM. Its gravity holding MW. **DM halo** shape **oblate spheroid**, size $\gtrsim 100$ - 120 kpc (Magellanic clouds in it). **Short/long axis ratio: 0.8**.

Light comes from stars in disk. **Spiral arms** contain hot young forming stars (e.g. HII regions, groups of bright O and B stars called OB associations, metal rich and young stars, age < 10^8 yr). They show rotation. Sun rotates much faster than apparent speed of arms. At center a spheroidal shape, called **Bulge**, with higher concentration of stars (**$M_{bulge} = 10^{10}\ M_\odot$**) likely elongated: MW is **barred spiral galaxy**, bar size 6 kpc (thickness at least 2 kpc).

Stellar halo spheroidal shape, different population of stars. Mass in stars of the halo **$M_{halo} = 10^9\ M_\odot$**, stellar density much lower ==> stars harder to see. Gas density very low. Size likely beyond 20 kpc from center. **Beyond 15 kpc from center, gas density drops, stars don't form.**

Stars in bulge and halo older than in disk. Gas and stars mainly in disk, with thickness of 300 pc. Very hard to observe galaxies behind disk through **zone of avoidance** (15° North and South of Galactic plane). Infrared (IR) observations more effective.

Thousands of **open clusters** in MW (few pc size) with hundreds of stars. Short life, a few 10^6 to 10^9 yr before **evaporation** (stars dispersed). Mostly in arms, showing short life.

OB associations diameters of ~100 pc with high concentration of 10-100 stars with spectral class O and B. Centers contain open star clusters. Age is a few 10^6 yr. About 70 known in MW, mostly in spiral arms

Globular clusters (GCs): clusters with mass **10^4 – 10^6 $M_\odot$ in stars**, sphere of around 50 pc diameter, distributed spherically around MW center, 2/3 in Galactic halo, here are 1% of stars in halo. Their distribution is indication of shape of stellar halo. Mainly old stars, at leat 160 GCs known in MW (perhaps 10 – 20 more still undiscovered). **Density of stars at GC center typically 10^4 pc^{-3}** (10^5 × larger than solar neighbourhood: ~ 0.1 - 0.2 pc^{-3}, distance to nearest star Proxima Centauri 1.3 pc).

Stellar generations (populations) identified by age, chemical enrichment (called metallicity) and location in galaxy. (For the Sun, metallicity $Z_\odot$, defined as the ratio of mass of particles heavier than helium over total mass, is $Z_\odot = 0.014$.)

Population I: stars mainly in disk, can be young, but also 10^{10} yr old. High metallicities, generally $Z = 0.01 - 0.04$. Circular orbits around center. The Sun is a Pop I star.

Population II: mainly in halo and bulge, oldest ($12–14\times10^9$ yr). No much gas in these regions. Low metallicities, $2\times10^{-6} < Z < 0.002$. But some stars in bulge have solar metallicity. Orbiting at **higher speed than disk stars**, around galaxy center, in eccentric orbits. Not ordered motion, half in **retrograde** orbits (half in one direction, the other in the reverse direction).

Population III stars, first generation of stars, from primordial gas, lowest metallicity $Z < 10^{-9}$, lithium is the other chemical element present. Never detected/observed so far.

Different metallicities measured in stars with different ages allow to track history of different stellar populations ==> formation history of Galaxy.

Mass of the Milky Way

Sun's velocity measured in 1920s, using Pop II stars in the halo as references. Mass of the Galaxy measured using **rotation curve**: speed of different objects measured as a function of distance from center.

Laws of gravitation of one body rotating around another body allows to determine mass of central body. For simple configuration of two bodies system, where $M >> m$ (Newton's laws):

$$F = a\,m = G\,M\,m\,/\,r^2 \qquad (1.1)$$

$$\Longrightarrow a = G\,M\,/\,r^2$$

Centripetal force of body m moving at constant speed v :

$$a_{cen} = v^2\,/\,r \qquad (1.2)$$

If this is due to gravitation ==> $a_{cen} = a$, therefore:

$$v = (GM/r)^{½} \propto 1/r^{½} \qquad (1.3)$$

From which one can determine mass of larger body:

$$M = v^2 r/G \qquad (1.4)$$

(From this, easy to estimate an accurate value of Sun's mass using planets in solar systems – **Keplerian orbits**.)

For an approximate calculation of mass of MW inside Sun's orbit, we assume that mass in the Galaxy spherically distributed, outside Sun's orbit, the mass doesn't affect the Sun, and mass inside Sun's orbit is concentrated in Galaxy Center. Sun's distance from Galaxy center is 8.5 kpc. Then Eq. 1.4 gives mass inside r:

$$M_{\mathrm{MW}}\ (r = 8.5\ \mathrm{kpc}) = 1 \times 10^{11}\ \mathrm{M}_{\odot} \qquad (1.5)$$

using that $v = 240$ km/s. Outside Sun's orbit, same principle to determine total mass of MW. Difficult to find where MW ends. Taking different objects at different distance and rotation velocity, we get **rotation curve** of MW. To determine the rotation curve of the Galaxy, stars are not used due to interstellar extinction. Instead, **21-cm maps** of neutral hydrogen are used. Rotation curve of the Galaxy stays flat out to large distances ==> mass of the Galaxy increases with increasing distance from the center: $\boldsymbol{M(r) = k \times r}$, where k is a constant.

Flat rotation curve gives lower mass density in outer region. If MW was confined in small volume, we would detect decline of rotation curve. **Decline of rotation curve never observed** up to distance of 20 kpc from Center. Size of MW can't be defined. Substantial contribution to mass is from from a matter that doesn't emits light (**dark matter**). **Mass of MW is also determined using GC, halo stars and nearby galaxies**.

No more than **30-50% of mass in the disk is DM**, visible matter dominates. In optical images, star view blocked by dust. In near infrared (NIR), much less severe. In far IR (FIR), dust emission is dominating. In radio, gas emission shows extend of galaxy.

Cross section through disk

Thin & thick disk: the inner and outer part of the disk. Thick disk contains older more metal poor stars, formed earlier than thin disk stars.

Number density of stars, moving out of mid plane:

$$n(z) = n_o\, e^{-|z|/h} \qquad (1.6)$$

where z is distance from plane, h is **scale height** characterizing thickness of disk, n_o mean number density at the plane. In various scientific contexts, a **scale height** is a distance over which a quantity decreases by a factor of number equivalent to *e* (approximately 1/2.71828 = 0.37). **At distance of z = *h*, number density is e^{-1} n_o = 0.37 n_o.** Scale height is relative parameter different for different classes of objects. Consequence of this definition: MW doesn't have a defined border (*n* never goes to 0).

Stars in thin disk with spectral class G or smaller stars, $T < 6000$ K, are distributed with ***h = 300 pc**.* For Eq. 1.6, G stars of thin disk at 1 kpc from plane would have number density *n* about 4% of density at the plane.

O and B stars (young & massive) in plane have ***h = 50–60 pc***. These stars form in the plane, then they get scattered at higher height with time, due to gravitational interaction with molecular clouds of mass $10^7\,M_\odot$.

Stars in thick disk with spectral type below G have ***h = 1000 – 1300 pc**.* Less common in plane than in the thin disk. Number density in thick disk overcomes the one of thin disk at larger distances. Not known why these two different populations.

For **ISM**, density of gas ρ is used:

$$\rho(z) = \rho_o\, e^{-|z|/h} \qquad (1.7)$$

where ***h = 150 pc***, much more concentrated than thin G and K disk stars.
As OB associations are more concentrated than ISM, and OB number density proportional to star formation rate (SFR), then:

$$\text{SFR} \propto \rho^n \qquad (1.8)$$

where $n > 1$.

Spiral arms traced by SFR, for instance star forming regions (H II regions), OB associations, open clusters, dense molecular clouds. The Sun is located between two spiral arms. One piece of spiral arm found near Sun.

Spiral arms long-lived structures because very common in other galaxies, not made of same stars. This is easy to see, considering that stars have constant almost circular speed at large distances from center, $v \sim 200$ km/s. If arms follow stars ==> inner side of arms would make more loops than outer side, which is never seen in spiral galaxies.

Spiral density wave theory: spiral arms propagates like sound waves, not involving motion of mass (which moves faster than density waves), but motion on compression of gas where star formation is happening. This is how spiral arms become brighter than the rest of the galaxy. Theory developed by Lin & Shu still debated and not totally proven.

Stars and gas orbiting in ellipses. If ellipses oriented same way, smooth distribution. If each ellipses is rotated slightly with respect to nearby ellipses, **spiral arms develop** naturally. If pattern persists ==> **permanent pattern of density enhancement**, though stars and gas change position constantly.

Spiral density wave from non-axisymmetric matter distribution in galaxy, response to periodic perturbation on gravitational field.

Spiral density wave rotates around center and maintains its shape (like in solid body, speed decreases linearly with distance). Density wave speed slower than stars and gas for most part of the galaxy (going out, they are the same). Gas crosses density wave, gets compressed. **Star formation triggered in giant molecular clouds** ==> young luminous objects in spiral arms.

Halo and bulge

Old stars are in the halo, have low metallicity, elliptical orbits around center, often very inclined toward galactic plane. The strongly asymmetrical distribution of GCs was **used by Harlow Shapley in 1918 to assert the shape and dimension of MW**. **GC more concentrated toward direction of Sagittarius constellation** ==> this must be direction of MW center. Closer to center ==> metallicity is higher than 1/5 solar value ($Z > 0.003$, belong to disk 1/3 of all GCs), in halo $Z < 0.003$.

Many inside sphere with radius 20 kpc and centered at Galactic Center, a few beyond 37 kpc, none in between. **Hard to set the border of MW using GCs, individual stars are used instead**. Although fainter, they are many more, while GCs not so numerous.

Density of stars at center of GC typically 10^4 pc^{-3}. GC stars are the oldest stars in the MW, provide lower limit to age of universe. GC probably f**ormed before MW** totally settled. Age determined using HR diagram, as **stars formed all at same time, from gas with uniform chemical composition**. **Isochrones** plot is position of stars in HR diagram with same age but different mass. Position of **turn off point gives age**, using model calculations. Theoretical models very uncertain, **large uncertainty** due to convection inside stars.

Some GCs in halo a few Gyr older than others ==> halo didn’t form all at same time with gravitational collapse. Different regions formed at different times (**coalescence** of different clouds?). GCs also formed during collisions of different clouds?

Standard candles are used to determine distances of stars. For example, **RR Lyrae stars** (from the star *RR* in *Lyra* constellation). Fainter than Cepheids, RR Lyrae are post Main Sequence stars burning He (horizontal branch) in **instability strip**, are commonly found in globular clusters (while Cepheids are more common in the disk, younger stars). Absolute magnitude can be **$M_V \approx +5$**, they could be **seen to distance up to 100 kpc (visual apparent magnitude $m_V \approx 20.5$)**.

Number density of *RR Lyrae* stars drops with distance from Galaxy center as:

$$n(r) \propto 1/r^3 \qquad (1.9)$$

they are seen at least out to 30 kpc from center, similar to GCs. They have same age and metallicity ==> same population. **Maximum density of *RR Lyrae* stars marks galactic center**. This is **8.7± 0.6 kpc** from the Sun, consistent with what normally adopted of 8.5 kpc.

Galactic bulge

Hard to see in optical because of dust, seen in infrared (IR). Galactic bulge is 3 kpc in radius. Stars' age are as in halo (old), but **higher metallicity** ==> cosmic recycle very quick and efficient, thanks to much higher **stellar density**. Within a parsec of the galactic center, the estimated number density of stars is **$\sim 10^7$ pc^{-3}** (10 million stars per cubic parsec!).

Almost circular orbits different than stars in disk. Outer stars have $v = 100$ km/s. Star distribution asymmetric, indicating presence of **bar**. Computer simulations of stars showed that bars are **stabilizing structures**. Bar **develops from asymmetries, within a few galaxy rotations**, up to a certain size when accumulated mass of the bar compromises the stability of the bar structure (**bar instabilities**). Since so many spiral galaxies have a bar, it is likely that they are recurring phenomena. The oscillating evolutionary cycle **from spiral galaxy to barred spiral galaxy** is thought to take **on average ~ 2 billion years**. **At least 30% of all spiral galaxies have a bar** at the center.

Central Black Hole

The Galaxy Center hosts a massive black hole (BH). Mass estimate important for galaxy formation. Discovered using Newton's law of objects orbiting central mass.

In Galaxy center, **Sagittarius A*** (Sgr A$\ast$) is a strong radio source, thought to be the **center of our Galaxy** and containing a young star cluster (10^7 yr) within 0.04 pc (apparent size ~ 1 arcsec).

Motions of objects in small volume have been found to follow (Eq. 1.3):

$$v = (GM/r)^{½} \propto 1/r^{½} \qquad (1.10)$$

which is Keplerian speed. One star (*S2*) is mapped over 15 years of its orbit around *Sgr A*$\ast$. Speed of stars around center remarkably close to Keplerian speed with$1/r^{½}$ decline ==> high concentration of mass in center is dominating motion. Mass limit going inward indicates mass at center **$M_c = 4.1 \times 10^6\, M_\odot$** within 0.001 pc (206 AU) from center ==> likely **central BH**. Recent radio observations indicate emission coming from a region of size of about 1 AU = distance Earth–Sun. Which means radius of BH:

$$R_{BH} < 1\ \mathrm{AU} \qquad (1.11)$$

Extremely compact and massive ==> BH. The average **density** of this massive black hole is of the order of **the one of water on Earth**. Volume is proportional to R^3, but Schwarzschild radius is proportional to mass, thus density of a black hole is proportional to $1/M^2$. Therefore, **higher mass black holes have lower average density**.

BH exists in center of many other galaxies, possibly common feature in ALL GALAXIES. **Work in progress!**

Formation and evolution of MW

ISM key ingredient for evolution because here stars form and material returned when stars die. Little gas in halo. With **galactic fountain,** gas ejected from disk, caused by supernova (SN) explosions (gas can leave disk because gas density drops outside disk). Gas returns from halo (observed **high velocity clouds** from Doppler shift of 21 cm observations). Some of them are very far, 400 – 1000 kpc from MW.

Gas infall: 0.4 – 3 $M_\odot$ yr^{-1} (< 1.4 $M_\odot$ yr^{-1} from intergalactic medium). **Gas outflow: 3–10 $M_\odot$ yr^{-1}**. Net result: **gas leaving MW?**

Thick disk contains older more metal poor stars. Did they form in thick disk or thick disk formed after stars formed? Did halo stars form when MW forming, or joined halo later when MW already formed? Or left after encounter with small galaxies? **Key questions of galaxy formation & evolution**.

Galaxies merge. MW involved in collision right now with another galaxy (**Sagittarius Dwarf Elliptical Galaxy - SagDEG**). Discovered in 1994 (distance of 15 kpc from Galactic Center), unobserved until now because it is located in farthest region of MW. SagDEG enriched halo and Galactic Centre with stars. A possible closer galaxy to the Milky Way is **Canis Major Dwarf** (also known as Canis Major overdensity), discovered in 2003, distance from Galactic Center is 13 kpc, and 7.7 kpc from the Sun. The discovery as a possible disrupted galaxy is not yet confirmed.

2. NORMAL GALAXIES

Normal galaxies classified according to morphology (**Hubble classification**) **ellipticals** (60%, E0-E7, 3D ellipsoid), **spirals** (< 30% Sa-Sd, SBa-SBd). B denotes the presence of a bar, while a, b, c, d is based on the tightness of their spiral arms. **Irregular galaxies** are <15%. At least **30% of spirals are barred**. **Lenticulars** have disk but no arms. MW is SBc galaxy.

Elliptical galaxies have higher concentration of stars at center. Two observed axis *a* and *b*, parameter:

$$f = (a-b)/a \times 10 \qquad (2.1)$$

gives classification of ellipticals ***E0 – E7*, according to how flat the ellipsoid is**. Ellipticals with 3 different axis with different sizes are **triaxial ellipsoid**. **Spheroid** is ellipsoid with 2 axis of equal length (possibly majority of elliptical galaxies, more stable). Flattening is not due to rotation.

Dwarf ellipticals: $M \sim 10^{5-9}\,M_\odot$ **most common galaxies** in the universe today. Traditional evolutionary sequence (Hubble sequence) is wrong: spiral galaxies don't form from elliptical galaxies.

Angular momentum per unit mass is low in ellipticals and irregulars, higher for spirals (it goes up from Sa → Sd, or SBa → SBd) and lenticulars.

Gas-to-stellar mass ratio (gas in molecular and atomic form): in MW 10%. **5 – 15% in spirals** (Sa → Sd, or SBa → SBd). **15 – 25% in irregulars**. Neutral and molecular gas absent (~1%) in ellipticals, mostly ionized gas at $T = 10^6$ K.

Total (baryonic and dark) mass

Ellipticals...................	$10^5 - 10^{13}\,M_\odot$
Spirals.......................	$10^9 - 10^{12}\,M_\odot$
Irregulars...................	$10^7 - 10^{10}\,M_\odot$

Ellipticals have no or little on going star formation (SF), mainly old stellar populations.

Some galaxies have abnormal features, hard to classify (**peculiar galaxies**). See **M87** with jet originating from Active Nucleus (with supermassive black hole in the center), classified as **E0p**.

cD galaxies: giant elliptical galaxy at center of rich galaxy clusters (see Coma galaxy cluster). **Probably formed from merging of smaller galaxies**. Some cD galaxies have several bright spots near center, like galaxy nuclei, probably leftovers of absorbed galaxies (supporting merging hypothesis). cD galaxies are also frequently considered the largest galaxies.

Apparent surface brightness (for extended sources) is apparent flux density (energy per sec) seen per detector surface unit, measured in W m^{-2} $arcsec^{-2}$ or also in ergs s^{-1} cm^{-2} $arcsec^{-2}$ (or in *mag* $arcsec^{-2}$ in *V*-band around 5500 Å).

Isophote contours closed curves connecting regions with same apparent surface brightness. These contours don't mark end of galaxy, but reach noise level of detector. Luminosity of galaxy doesn't fade away so sharply as stars.

Galaxies of similar type (morphology & luminosity) have similar **surface brightness profile**. Then, it's possible to calculate total flux density, by measuring surface brightness in several regions and assuming to know surface brightness profile.

Necessary to correct for orientation, then get total flux. For spirals, angle derived **assuming intrinsic circular morphology**. Luminosity derived knowing distance. Linear physical diameter ℓ derived by extrapolating apparent diameter at given surface brightness. Then calculated with distance d of galaxy:

$$\ell = d \times \theta \qquad (\theta \text{ in radians}) \qquad (2.2)$$

where θ is apparent diameter of galaxy (in radians).

Mass of galaxies

Method 1: rotation curves of spiral galaxies similarly to what done for MW. Measurements of velocity at different distances compared with models. This gives total mass, including dark matter. This method has problems, e.g. it gives a lower limit of mass, since this is calculated for 'visible' component only. Also, **requires knowledge of galaxy distance**. Widely used.

Largest possible radius measured using 21 cm line & Doppler shift to measure velocity, with respect to us (radial component). Knowledge of galaxy inclination is required.

Method 2: velocity dispersion of elliptical galaxies. Global rotation relatively unimportant, stars move feeling each other's gravitational field. **Velocity dispersion** is velocity range of stars with respect to us (along the line of sight). **Virial theorem** gives M of galaxy with radius R and with velocity dispersion. From Eq. 1.3, we get:

$$\Delta v \propto (M/R)^{1/2} \qquad (2.3)$$

Δv can be measured using Doppler shift in many stars. Method gives reasonable results, but again lower limit because depends on observable stars.

According to the **virial theorem**, for a galaxy in a stable gravitational situation, kinetic energy of stars E_K is related to gravitational potential of stars E_g:

$$E_k = -E_g/2 \qquad (2.4)$$

In equilibrium condition, it is said that the galaxy is **virialized**.

Imagine cloud of stars with zero velocity. This has maximum E_g (0). As stars are released, E_k goes up (feeling gravitation field) and E_g goes down (conservation of E). Sum is constant (with 1/2 in it).

Method 3: X-ray emission of elliptical galaxies gives temperature, density and physical extend of gas. Temperature generally few 10^6 K (ionized gas). Larger extend and high temperature means high mass (large gravitational field) necessary **to prevent**

gas from escaping and keep galaxy in equilibrium. Mass measured with models, method also used for clusters of galaxies.

Many ellipticals show large X-ray emission, larger than stellar component.

Method 4 (baryonic mass, mainly stars only): composition of galaxies and stellar population synthesis models

In elliptical galaxies, gas mainly ionized. In giant ellipticals, ionized gas to total mass ratio similar to that in spirals (which is mainly neutral or molecular gas). Less ionised gas in smaller ellipticals. No neutral gas in ellipticals ==> no on going SF. Pop II stars dominating.

Difficult to determine properties of single stars in galaxies. **Stellar population synthesis models** are used on **composite galaxy spectra** to obtain global properties of stellar component. These are ***M, L, & M/L***. As seen from HR diagram, large contribution to stellar component is from cold & small stars (they live longer), more visible in NIR ==> spectra should include NIR component to compare with models.

In models, **stellar mass function** is used. Each star with given mass and chemical composition gives different spectrum. Combination of many spectra gives composite spectrum of galaxy. Many stars (each with luminosity L) are used to get best-fit of observed spectrum.

Distance of galaxies

Distance of galaxies *d* important to determine many physical parameters. First, this gives actual size of galaxy ℓ, given by:

$$\ell = d \times \theta \qquad (2.5)$$

where θ (in radians) is the apparent size of galaxies. Second, the distance is important to derive the actual spatial distribution of galaxies, third to investigate evolution of galaxies.

Almost all methods involve using **distance found from one method, to calibrate other methods**.

Method 1: geometrical method

Use apparent length of features with **known absolute size**. Then compare with **apparent size to derive distance**:

$$d = \ell / \theta \qquad (2.6)$$

For instance, Large Magellanic Cloud (LMC) distance determined with supernova 1987A. A bright ring highlighted by radiation emitted by SN, 3.5 years after explosion. From time delay between first and last spot of the ring which is illuminated, as observed from Earth, size of ring is de-projected, assuming circular geometry:

$$a = \Delta t \times c \qquad (\Delta t = 340 \text{ days}) \qquad (2.7)$$

Method 2: standard candle

Object with known luminosity:

$$d = (L / 4 \pi F)^{1/2} \qquad (2.8)$$

Often measured flux F affected by absorption. If not corrected, distance is overestimated. Main problem: standard candles have to be real standard candles.

Cepheid variables use period luminosity relation to get L. With *Hubble Space Telescope* (HST) up to ***d* = 30 Mpc**.

Method 3: known galaxy properties and relations

Surface brightness fluctuations in galaxies

For a uniform distribution of stars in galaxy, luminosity decreases with distance $1/d^2$. In pixel with finite dimension, number of stars depends on distance of galaxy. Two effects compensate each other and the mean flux in all pixels is equal. Fluctuations for nearby galaxy larger than for farther galaxy.

Differences are in real life generally small, **fluctuations of order of 1%**. This method gives distances for galaxies at distance **50 Mpc and more**.

Tully-Fisher relation

Relates luminosity L of **spiral galaxies** to their maximum rotational speed (empirical relation):

$$L \propto (v_{max})^4 \qquad (2.11)$$

More luminous (= more massive) galaxies have larger rotational velocity (to fight against gravity). Accuracy of the order of 15%.

Faber-Jackson relation

Same principle as before, but for **elliptical galaxies**:

$$L \propto (\Delta v)^4 \qquad (2.12)$$

where Δv is the velocity dispersion of stars in galaxy. Difficult to calibrate because hard to measure flux in elliptical galaxies. **Fundamental plane** used instead, which relates Δv to brightness of galaxy at some radius.

Method 4: redshift

Based on relation between distance d and Doppler redshift z due to cosmological expansion. For not large distances:

$$d \propto z \qquad (2.9)$$

Simple to use, depends on cosmological model (and Hubble constant).

One method at lower distance can be used to calibrate method and get larger distances (**distance ladder**). Today distances of remote galaxies ($d > 100$ Mpc) measured with uncertainty of 15%.

Hubble law

Doppler shift gives velocity of one object with respect to another. Expansion (recession) of the universe ==> **redshift**. Measured using set of lines (absorption or emission) with known rest-frame wavelength λ_{res}:

$$z = (\lambda_{obs} - \lambda_{res}) / \lambda_{res} \qquad (2.13)$$

z is the same for any line considered in the spectrum.

Hubble first established relation between redshift and distance of galaxies. This is called **Hubble's law** (distance-redshift relation):

$$z = H_o / c \times d \qquad (2.14)$$

where c light speed, $H_o \approx 69$ km s $^{-1}$ Mpc $^{-1}$ **Hubble constant** today. Eq. 2.14 is a linear approximation valid for **small redshift $z < 0.1$**. As $z = v / c$, then:

$$v = H_o \times d \qquad (2.15)$$

According to Eq. 2.15 a galaxy at $d = 100$ Mpc moves at speed of almost 7,000 km/s away from us. That is, **speed of recession proportional to distance**. Interpretation: every point is moving away from any other point, and speed is proportional to distance (universe is expanding). No point is the center of the universe. Determination of Hubble constant one of major problems in astronomy.

Hubble constant measured plotting redshift of galaxies vs. distance, determined using standard candles. Scatter of this plot also due to proper motion of galaxies, independent from cosmic expansion. Eq. 2.14 **unreliable for distance $d < 40$ Mpc or $z < 0.01$**.

Supernovae Ia easy to discover because bright. All SN Ia have approximately same luminosity. When WD exceeds Chandrasekhar limit $M > 1.4\ M_\odot$, C and O undergo rapid thermonuclear burning ==> SN. This limit ensures that luminosity is constant.

Method of great value and importance for cosmology.

Supernovae II based on relation between L, T and R for black body (BB):

$$L = 4\pi R^2 \sigma T^4 \qquad (2.10)$$

$\sigma = 5.67\times10^{-8}$ W m^{-2} K^{-4} Stephan-Boltzmann constant. SN treated as BB. T can be determined from spectrum. R to be measured from observations.

Formation & evolution of galaxies

How do galaxies form & when? Why their morphology? Stars formed before the galaxy? All these processes not fully understood. One thing known: galaxies didn't form all at a single time, and then evolved.

However, when **observing galaxies at higher redshift**, it is possible to **go back in time**, when universe was very young. Most distant galaxies known at $z \sim 11.09$, when universe was 0.4 Gyr old, ~ 3% of present age.

Complementary approach: to model theoretically history of formation of galaxies.

- Galaxies formed after **Big Bang** (13.8 Gyr ago);

- Since then, universe is expanding, which is not constant with time;

- Due to expansion, the universe gets larger, colder and less dense;

- Matter was initially almost uniformly distributed;

- Protons, neutrons and electrons formed from more fundamental particles, universe has no net electric charge;

- In first few minutes, He nuclei formed from protons (24% of total baryonic matter);

- 80 - 90% of matter of unknown nature (non baryonic), and dark, but sensible to gravity;

• Small fluctuations of matter density (non-uniform matter distribution) gave gravitational instabilities ==> seeds for the formation of gravitationally collapsed objects (stars, galaxies, quasars...).

Galaxies formed from **fluctuations in matter density** created in primordial universe. Despite expansion, gravity worked against expansion on small scales (**gravitational instabilities**). Collapsing clouds (**mainly dark matter**) *seeds* of galaxies & clusters of galaxies. Baryonic matter are emitting radiation through stars.

How galaxy formation proceeded is not totally understood, different possible scenarios. Depends on scale of collapsing clouds and nature of non-baryonic matter.

For **Cold Dark Matter** (**CMD**, non relativistic particles, speed $\ll c$) ==> **first structures formed have $M \sim 10^6 M_\odot$** (like large globular clusters). Bigger galaxies formed later from merging of small galaxies. This is **hierarchical scenario** (or **bottom-up scenario**).

For **Hot Dark Matter** (**HDM**, relativistic particles with $v \sim c$) ==> **density fluctuations harder to grow**, first structures much larger, first galaxies would form from these large structures (**top-down scenario**). Large structures would develop in clusters of galaxies.

Current more favored scenario is CDM model. Computer simulations can model galaxy formation and evolution and explain observed distribution of galaxies over time.

If elliptical galaxies formed from merging of small galaxies, how disks of large spirals formed from small first collapsed structures is not totally clear. Plus, **large elliptical galaxies are present in the past history**, **CDM model not able to form them so early on**.

Possible small spheroid forms first (like a bulge today), then disk forms later from infall of gas (with angular momentum) from regions surrounding spheroid, in the case the galaxy is isolated for long time. **Merger tree** shows how to form large galaxies from small galaxies.

Evolution of isolated galaxy depends on star formation rate (**SFR**) and evolution of stars in galaxy. SFR evolution strong function of morphology of galaxy. Ellipticals & bulges have old stellar populations, SFR much higher in the past. SFR evolution gets flatter for spirals (larger gas content) from Sa type to Sd type.

Caution: stars in elliptical galaxies might have formed in different locations than present location.

Interactions and mergers in galaxy evolution

Today number of **interacting galaxies** locally is a few % for bright galaxies ($L > 10^{10} L_\odot$). Mergers are site of intense star formation. Computer simulation of interacting galaxies started in the '70s (by brothers Alar & Juri Toomres) and today very successful.

Interactions triggering star formation, which can also **be quickly quenched by the same process** (it can suppress star formation after initial burst) **due to strong winds caused by SN explosions** (these remove gas). Often these are **starburst galaxies**. Strong UV emission is absorbed by dust and re-emitted in IR. Shown by IR image of Antennae galaxies (half of total energy radiated in IR). IR emission doesn't peak at location of UV emission.

Galactic mergers take tens/hundreds of 10^6 yr. Some galaxies show evidence of past collision ==> elliptical galaxies result of merging?

Elliptical galaxy **NGC 4365** is probably result of merging, though this is not obviously shown by galaxy image. Galaxy rotating around major axis, but core rotating around perpendicular axis. **Galaxy result of merging of 2 galaxies** with perpendicular rotating axes. **Stars in two systems have same age** of 12×10^9 yr. **Merging might have occurred at that time**.

Observations of galaxy evolution

Deep fields show galaxies farther away ==> we see past history of the universe. A galaxy at redshift $z = 5$, observed in visual (V) band $\lambda_o = 5500$ Å, corresponds to rest frame **far UV** at $\lambda_r = 5500/(1+z) \simeq 900$ Å. **At high redshift, galaxies**:

- are red and small because large distances, UV absorption from intergalactic gas & redshift;

- had very irregular morphologies;

- different bands have different appearance;

- after correcting for redshift, they are in the past more UV bright than today ==> more star forming.

Today irregular galaxies are generally small and in number only less than 15% of total. A few percent for galaxies are as large as MW. In the past, irregulars are likely more than 25%. This research field still not fully understood.

Rest frame UV light provides rate of SF in a galaxy. If we want to estimate SFR with UV observations, it is necessary to correct for dust extinction.

In cosmology, to define distances between objects two quantities are used. The **comoving distance** is the observed length (**proper distance**) divided by expansion rate:

$$\ell_c = \ell/(1+z) \qquad (2.16)$$

Proper distance *(*also called physical distance) corresponds to where a distant object would be at a specific moment which changes over time due to the expansion of the universe. ***Comoving distance*** factors out and does not change in time due to the expansion of space. **SFR density of the universe** (after correction for dust absorption - very uncertain) is the SFR in the history of universe per Mpc^{-3} (in comoving volume). Much higher in the past than today, maximum reached at $z > 1$.

Galaxy spectra

In spectra of galaxies, hot gas gives emission lines, stars give absorption lines from atmosphere. Together give information on the nature of galaxies. For example, chemical composition.

Doppler broadening (motion of atoms) of spectral features Δv gives information on temperature of gas:

$$\Delta\lambda/\lambda = \Delta v/c \qquad (2.17)$$

where λ is rest-frame wavelength of observed line, $\Delta\lambda$ is the observed width of emission line. Velocity dispersion gives gas temperature:

$$\Delta v \approx (2kT/m)^{1/2} \qquad (2.18)$$

where k is Boltzmann constant and m is average mass of atoms. For same T, Δv is smaller (narrower lines) for heavier atoms.

Line broadening also from **bulk motion** (motion of gas cloud on large scale). Rotating galaxies have lines broadened of $\Delta v = 100 - 300$ km/s, much larger of thermal broadening in stellar photosphere.

Thermal broadening is different for different lines, bulk motion broadening same in all lines.

Star forming regions show forbidden lines, possible for low gas densities.

Doppler shift of lines gives information on dynamics in the galaxy (stars are moving), temperature of gas, velocity relative to MW.

Star forming galaxies have strong emission lines coming from hot gas ionized by young stars (HII regions). **Starburst galaxies** have this kind of spectra.

Elliptical galaxies show many absorption lines, from photosphere of generally old stars. Lines are broader and shallower than in individual stars, because result of many stars with different velocity. No HII emission. **Spectrum similar to that of K star**, because cool giant stars dominate.

Spiral galaxies have stellar continuum with shallow absorption lines and weak emission lines. Mix of properties of elliptical and irregular galaxies.

F_λ flux emitted per wavelength unit by galaxy on large wavelength interval (**broadband**). F_λ in radio energies is generally much smaller than F_λ in other bands, because flux measured per wavelength unit (λ large in the radio). Flux is often represented in terms of λF_λ (in W m^{-2}) because this represents better energy emitted. Called **Spectral Energy Distribution** (**SED**).

3. ACTIVE GALAXIES

Active galaxies show extra emission of radiation, other than from stars, released from very small regions at the center of galaxies, called **active galactic nucleus** (**AGN**). Many different classes of AGNs (Seyfert galaxies, radio galaxies, quasars) all have in common **power coming from central supermassive black hole (BH)**. Different L (different central mass and accretion rate) and orientation.

Rare in local universe, more abundant in the past, seen in old galaxies. Maybe either all galaxies had short active phase, or only small fraction active for a long time. AGN have $\boldsymbol{L > 10^{11} L_\odot}$ emitted in a region a little larger than region containing solar system. Power coming from accreting region around **massive BH**. $\boldsymbol{E_g}$ **converted into radiation**.

Active galaxies have very broad emission lines (several thousand km/s), more than starburst galaxies. Not coming from thermal broadening (T too large, gas would be totally ionized) ==> bulk motion of gas.

General names of AGN: **quasar** (Quasi-Stellar Radio Sources) or **QSO** (Quasi Stellar Object). Initially appeared as point sources, as stars.

3C 273 first quasar ever discovered in 1963 ($z = 0.158$, $d = 749$ Mpc). Optical magnitude $m \sim 12.9$, one of brightest (apparent) AGN. Its spectral energy distribution (SED) is much flatter than in normal galaxies ==> much more X-ray and radio flux. Peak in X-ray/UV (some AGNs have **big blue bump**). Energy not coming from stars only.

Different types: **Seyfert galaxy** are mostly spiral galaxies with very bright nucleus, (e.g. in far IR). Variable emission ==> small region, shorter than length $\Delta t \times c$. Strong emission lines. Unlike quasars, their host galaxies are clearly detectable. They are closer and fainter than quasars. **10% of all galaxies in the nearby universe have a Seyfert** at the nucleus. **Type 1 Seyferts** have narrow lines ($\Delta v = 400$ km/s) and broad lines ($\Delta v = 10{,}000$ km/s). **Type 2 Seyferts** have only narrow lines (broad lines, if present, very weak) due to obscured dusty torus oriented along the line of sight.

Quasars (or QSOs) are the most luminous and distant active galaxies known. Appear as radio & optical point-like sources with unusual optical spectra. Emission lines are redshifted. **Today more than 200,000 QSOs known**, the highest redshift $z = 7.54$ (seen as it was 699 Myr after Big Bang). If seen at these large distances, they must be very luminous.

Composite spectrum of quasars (spectra of hundreds of quasars summed together), mainly high redshift objects ==> UV lines. Strong Lyman-α line of hydrogen ($\lambda = 1215$ Å).

10% of all quasars are radio loud (strong radio emission). The rest are **radio quiet** (weak radio emission). **Many QSOs are variable sources**, on scale of months to days. **Many radio QSOs have prominent jets** of material from central source. Some (3C 273) visible also in optical.

Galaxies hosting QSOs not easy to detect. QSO too bright. Not clear relation between QSOs and host galaxy morphologies. Elliptical and interacting galaxies tend to host radio loud quasars.

Radio galaxies discovered accidentally by military radio antennas during World War II, dominate the sky in radio wavelength. Radio emission in two large regions (**radio lobes**) symmetrically located far from galaxy center. Brightest radio galaxy (one of the brightest radio sources in the sky): **Cygnus A**, radio lobes connected by jets, driving material from nucleus. Common in radio galaxies. This galaxy doesn't look in the optical like a quasar, but the nucleus have SED similar to AGNs. Spectra with large emission lines.

Nearest radio galaxy: **Centaurus A**. Apparent radio lobes extension is 9 degrees. Morphology of giant elliptical (or lenticular?) galaxy, bisected by dust lane (strange for an elliptical galaxy, they don't have dust). Thought to be result of merger of spiral (with dust) and elliptical. **M87** other famous radio galaxy, host is elliptical galaxy.

The central engine

AGNs point-like sources, even when observed with HST (resolution of 0.05") ==> AGN's apparent size < 0.05". Upper limit to size from **nearest AGN known**, NGC 4395 (Seyfert galaxy, $d = 4.3$ Mpc). For a size 0.05":

$$\ell < d \times \theta \qquad (3.1)$$

(θ in radians), 0.05" = 2.4×10^{-7} rad. For NGC 4395, $\ell < 1$ pc.

More constraining approach: time variability. Most AGNs variable over time-scale of 1 year. Many over 1 day. Time variability means size of source can't be larger than space travelled by light over time-variability interval:

$$R < \Delta t \times c \qquad (3.2)$$

If size larger, variability in different regions would mix (as seen from Earth), due to finite speed of light, we wouldn't see so distinct variability.

X-ray variability of **MCG-6-30-15** (time between peaks where radiation intensity doubles) is $\Delta t = 10^4$ s (few hours) ==> $\boldsymbol{R < 1\times10^{-4}}$ **pc** (20 times Earth–Sun distance, **Uranus - Sun distance**, 3×10^{12} m). It would fit inside solar system. Variability longer in IR, limit would be larger, indicating size of emission depends on wavelength.

In optical, luminosity of AGN in Seyfert galaxy is as the one of entire galaxy. **AGN radiates 3 times more in UV and radio** than the host galaxy ==> **AGN at least 4 times brighter than host galaxy**. Quasars much brighter. For radio galaxies, optical luminosity of AGN not so high, but mechanism producing bright radio lobes indicates central engine much brighter than seen. Not seen for effect of strong dust obscuration.

Luminosity of AGN can be larger than luminosity of normal galaxy, like MW:

$$L_{\mathrm{AGN}} > 2 \times 10^{11}\ L_{\odot} \sim 8\times10^{37}\,\mathrm{W} = 8\times10^{37}\,\mathrm{J/s} = 8\times10^{44}\,\mathrm{ergs/s} \qquad (3.3)$$

emitted in very small volume. Typical AGN's luminosity: $L_{\mathrm{AGN}} = 10^{38}$ W.

Small volume and large radiation power ==> central engine **supermassive BH**. Surface of BH called **event horizon**. **Schwarzschild radius**:

$$R_S = 2GM/c^2 \qquad (3.4)$$

when escape velocity exceeds speed of light. All radiation emitted is coming from outside event horizon, in regions few times larger than R_S. If $\boldsymbol{R_S}$ **is 10 times smaller** than what estimated in Eq. 3.2 ($R_S = 3\times10^{11}$ m), then **possible mass for massive BH**:

$$M_{\mathrm{BH}} = c^2 \times R_S\,/\,(2G) = 1\times10^{8}\,\mathrm{M}_{\odot} \qquad (3.5)$$

This is indeed typical mass of BH in AGN.

Gas clouds around BH move like planets around Sun (Keplerian orbit). Accelerated toward center. Collisions between clouds ==> **kinetic energy converted in heat**, gas T goes up. Collisions trap clouds inside orbits around BH ==> clouds closer to BH move faster. Friction (viscosity) between clouds ==> heat. Energy lost ==> clouds go closer. **Accretion disk** develops. Clouds with high T (from E_k and viscosity) emit radiation.

Spiraling-in of gas in accretion disks ends abruptly at distance a few times R_S (up to ~ 5×). Then gas infalling rapidly into BH. E emitted by accretion disk (AGN power) much higher than radiation from stars. **Most radiation from** $\boldsymbol{R}$ **= few ×** $\boldsymbol{R_S}$.

From calculations, mass m falling in BH radiates $\boldsymbol{E = 0.1\, mc^2}$ (10% of its rest energy). **Most efficient process converting** $\boldsymbol{m}$ **into** $\boldsymbol{E}$**, after matter-antimatter annihilation**. E of nuclear fusion of 4 protons into He only 0.7% of rest energy.

Energy radiated depends on **mass accretion rate Q** (in kg/s)*:*

$$L = 0.1 Q c^2 \qquad (3.6)$$

for $L = 10^{38}$ W, $Q = 10\ L/c^2 = 10^{22}$ kg/s = 0.2 $M_\odot\ yr^{-1}$. Gas provided by galaxy (MW has $10^{10}\ M_\odot$ of gas).

AGNs emit extra component in the radio by synchrotron radiation (non-thermal), due to relativistic electrons that spiral (hence non-zero acceleration) through magnetic fields. Synchrotron radiation is polarized.

Jets shown by quasars and radio galaxies **up to several hundreds kpc from center**. Streams of energetic particles along rotation axis of accretion disk, at **speed close to *c***. **Mechanism not fully understood**. Disk thicker close to BH forms pair of opposed funnels aligned with rotation axis. **This geometry and strong radiation pressure can cause acceleration** of material along rotation axis. E produced not enough. Recent models include **strong magnetic field** in disk to produce jets. Not fully satisfactory.

In radio galaxies and quasars generally one jet only is visible, though two exist. **Relativistic beaming** according to which radiation mainly emitted in direction of motion. **Jet points towards us brighter** than that moving in opposite direction.

Central region surrounded by clouds of gas and dust with shape of **torus**, oriented very likely as accretion disk. Gap in between occupied by clouds which give broad lines (**broad line region**). Clouds inside torus forming **narrow line region**.

Central engine emits UV and X-ray radiation (big blue bump). This absorbed by torus of gas and dust and re-emitted in IR. **Dust grains sublimated at $T = 2000$ K**, cloud's T must be smaller. At this T, and if dust emission as in BB, **radiation peaks at λ = 1.5 μm**. **Gas at lower *T* radiates more in IR**. Variability of torus much slower than accretion disk because size much lager. For typical L, inner edge of torus $10^3 - 10^4$ times larger than accretion disk.

Generally torus not resolved in observations. Disks on larger scales observed, provide supply of material to central engine.

Spectacular example: elliptical radio galaxy **NGC 4261** 29 Mpc away. Axis of radio lobes aligned with axis of accretion disk. Dark disk is 250 pc, central engine sub-parsec size.

Emission lines are those of atoms expected for cosmic chemical composition of gas: H, He, O, C, Si, N. Broad and narrow line regions (**BLR** and **NLR**) are characterized by large and low gas density. **Large width gives large motion**, presence of **forbidden lines means low density**. BLR are denser and move faster than NLR.

Motion due to gravitational field ==> **BLR closer to central engine** (inside torus). From line width, **typical speed of gas clouds $v \sim 5000$ km/s**. Radiation from central engine ==> $T \sim 10^4$ K. **BLR contains 10^{10} clouds covering 10% of the sky** (covering factor). **Mass of cloud $M < 10$ M$_\odot$**. Depending from orientation, BLR not seen because covered by torus.

Orbital speed for **NLR** clouds of **200 – 900 km/s** ==> **much farther away**, outside torus ==> can be seen much more than BLR. NRL **illuminated from central engine ==> not detected if torus behind**. NLR gets shape of cones originating from central engine. Extends to several kpc.

Unified model

Observations can be explained by orientation of accretion disk with respect to our view. Seyfert 1 & 2 are same objects, but **Seyfert 1** seen with rotation axis pointing not too far from our sight line, **Seyfert 2** seen with torus oriented such that central X-ray and optical emission hidden by gas and dust in torus.

Radio quiet quasars are like Seyfert 1, but **much more luminous**.

Narrow line radio galaxy is like Seyfert 2 with radio lobes. Approaching jet angle, broad lines detected ==> **Broad line radio galaxy** (one jet brighter than the other). Closer to jet angle ==> **Radio loud quasars** with one visible jet. **Blazer** if torus face on, characterized by **strong variabilit**y on very short time scales (**days or less**), over large wavelength range.

Why some AGNs are radio loud while most are radio quiet? **Radio quiet** AGNs more in **spiral galaxies**, whereas **radio loud** AGNs **in ellipticals**. Radio jets present if angular momentum of BH very strong. Could be the result of merging process of two massive BH from two galaxies.

Where are they now?

Not known how supermassive BH formed, closely connected with galaxy formation. **Galaxy interactions more common in the past, important processes to form supermassive BH**. Today 15% of Seyferts have companions, to be compared with 3% of normal galaxies. **Centaurus A is elliptical galaxy with AGN which is the result of recent merger**.

In comoving space, number density of most luminous AGN (QSOs) at maximum for $z = 1.5 – 2$ (9.5 - 10.5 Gyr ago) then declined by factor of > 100 today ==> short lived for cosmic standard. Fainter AGN declined later and more slowly. Where are they now?

Many normal galaxies would probably have a ***dead* (or *relic*) BH**. **Seen in MW** ($M = 4{\times}10^6$ M$_\odot$). Possibly also **in Andromeda** ($M = 3{\times}10^7$ M$_\odot$). Several more in nearby galaxies.

Modern view: **most galaxies have central black hole**. Maybe dead quasars? Scenario not yet proven. **Why quasars die**? Rate of accretion in typical AGN $< 1\ M_\odot\ yr^{-1}$ only, **no lack of fuel**.

Maybe (not proven) BH activity removes gas all around, not replaced by surrounding material. Possible that merger events switch on AGN (see recent merger of Centaurus A). **One day central BH of MW light up by merging processes?**

4. SPATIAL DISTRIBUTION OF GALAXIES

MW has at least 14 dwarf satellite galaxies. It is in the **Local Group** (more than 60 galaxies within ~ 3 Mpc) gravitationally bound. Largest galaxy Andromeda (most distant object visible with naked eye, $d = 0.8$ Mpc). All other galaxies are smaller. The Triangulum Galaxy (or Pinwheel Galaxy) is the third largest and only unbarred spiral galaxy in the Local Group. Next largest: Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC). **Other galaxies are with a few % of MW mass**. **Dwarf ellipticals** are faint, hard to find, possibly the majority, **more than 30 galaxies in Local Group**.

Clusters of galaxies

Galaxies not distributed randomly. **Clusters** also size of few Mpc, but many more galaxies than groups (**up to a few thousands**).

Closest galaxy cluster: **Virgo cluster**, irregular shape distance of 20 Mpc, **about 1500 galaxies**, mix of elliptical galaxies (more centrally located) & spiral galaxies (also at large distance from center). The cluster forms the heart of the larger **Virgo Supercluster (at least 100 galaxy groups and clusters within 33 Mpc)**.

Coma cluster: spherical shape, distance of 102 Mpc, > 1000 galaxies, mainly ellipticals. This is part of the Coma Supercluster, the neighbour of the Virgo Supercluster.

Galaxies that are not in clusters are called **field galaxies**. **Thousands of clusters known**. Number of galaxies gives **richness**. Clusters not randomly distributed, bigger structures exists ==> **supercluster**

Formation and evolution

Interactions (merging) between galaxies very important, due to high density of galaxies. More evident in the past. **Elliptical galaxies, very abundant in rich clusters**, **support this idea**. Possible that **clusters formed from merging of subclusters**. Merging of clusters observed, equilibrium state not reached.

Mass of clusters

Method 1: as for elliptical galaxies and **Virial Theorem** (Eq. 2.3):

$$M = (\Delta v)^2 R/G \qquad (4.1)$$

where Δv velocity dispersion of galaxies and $R \sim 2$ Mpc. System **should be *virialized*** (in equilibrium, not expanding, nor contracting), state achieved some time after cluster formation. **For first time** it was found that mass much larger than visible light ==> **dark matter dominates (70% – 90%)**.

Method 2: clusters are among strongest **X-ray emitters**, due to **hot gas**. **$T = 10^7 - 10^8$** K ==> $E = 1 - 10$ keV ==> **thermal bremsstrahlung** emission (broad continuum).

Bremsstrahlung in hot low density gas (**plasma**): **electrons deflected** by ions in the gas emit photons.

Ions form very low density **ICM**. Density and T measured from X-ray observations. For **hydrostatic equilibrium**, **gas pressure balanced by gravity**. **Typical total cluster mass $10^{14} - 10^{15}$ M$_\odot$**, much more than luminous matter. Baryonic mass of ICM 10% – 25% of total mass. **Mass in galaxies is < 10% of total mass**.

Method 3: light behind clusters deflected because of **gravitational lensing**. Background galaxies show different position, images brighter and distorted. Amount of distortion **depends on cluster mass** (lens). Complicated modelling, easier for symmetric distribution of mass. If source and lens aligned ==> **Einstein ring**.

Size of ring larger for more massive lens. Apparent radius of ring:

$$\theta_E = \{(4GM/c^2) \times [D_{LS}/(D_L D_S)]\}^{1/2} \qquad (4.2)$$

where D_{LS}: distance galaxy-lens, D_L: distance lens from Earth, D_S: distance galaxy from Earth. From Eq. 4.2 mass can be derived.

More than 50 gravitational lensing detected, where the lens is a cluster. Typical total cluster mass $10^{14} - 10^{15}$ M$_\odot$.

Large scale structure

Local group and nearby clusters form **Local Supercluster**, center is Virgo Cluster and 30 Mpc in size. Not virialized system. Other superclusters farther away. Large scale observations show structures even on larger scales, with voids and filaments connecting superclusters. **Universe can be considered uniform for scales > 200 Mpc**

Whole sky contains 41,253 square degrees. The **Hubble Ultra Deep Field** detected ~ 10,000 galaxies in 2.4×2.4 arcmin^2. If we consider the entire sky, in principle we could **easily detect ~ 2×10^{11} galaxies**. Not done because it would take too long for HST.

Intergalactic gas and dark matter

Their distribution much smoother than galaxies. Away from rich clusters, gas not so hot to emit in X-ray. Can be detected as Lyman-α forest: absorption of neutral gas in the **intergalactic medium** (**IGM**), with $T \sim 10^4$ K.

High-redshift quasars used as background sources. Their spectra show large number of absorption lines from discrete clouds in IGM. Different redshift, due to universe expansion. Sizes of several hundreds kpc.

IGM mostly ionized. Small fraction neutral, detected thanks to large size of clouds. Lyman-α most common line, $n = 1$ --> $n = 2$ energy-level transition (1 photon absorbed). Quasar photons absorbed at shorter and shorter wavelengths (higher energies) in observed spectrum, due to cosmological redshifts. This is why the forest is observed.

At larger redshift, **number Lyman-α absorption higher** because in the past the **universe was smaller** and **hydrogen was more neutral** (it disappears with time because it gets ionized by UV photons produced by new stars and galaxies).

Lyman-α clouds low density, don't form galaxies. Occasionally quasar sight line crosses a galaxy ==> Lyman-α absorption much stronger (damped Lyman-α systems).
In early times H mostly neutral. Lyman-α leftover of epoch after ionization (called **epoch of reionization**, see also Chapter 6). This sets time when first collapsed objects formed (stars, galaxies and/or quasars?). From observations, reionization happened for $z > 7$.

5. COSMOLOGY: ORIGIN AND EVOLUTION OF THE UNIVERSE

Earth is not in privileged position of universe (**Copernican principle**). Every point equivalent to any other.

Most common baryonic matter in universe in form of hydrogen and helium (today almost totally ionised, plasma). In mass $m(\mathrm{H}) \approx 75\%$, $m(\mathrm{He}) \approx 25\%$. Matter (e.g. affected by gravity) in universe dominated by dark matter (not emitting photons) of unknown nature. **Mostly non baryonic (baryonic matter is about 1/6 of total matter, which is dominated by dark matter).**

Background radiation: same radiation coming from any point in space, spanning γ-ray to radio wavelength, it's cosmic. It peaks at microwave, called **Cosmic Microwave Background** (**CMB**). Discovered in 1965, gives **great support to theory of Big Bang Theory**. Dominant (in terms of energy) form of radiation.

Cosmological principle: universe uniform on scales larger than several hundreds Mpc = $1/10^6$ of total volume of universe (homogeneous & isotropic). Mean **pressure *p*** and **density *ρ*** at given time equal in any point of the universe. Also proven by large uniformity of CMB, a few $1/10^5$ (in temperature), and galaxy and quasar distributions on large scales.

Universe is expanding, recession velocity is linear function of distance, valid for $z < 0.1$:

$$z = v/c = H_o d/c \qquad (5.1)$$

is Hubble's law. **H_o represents rate of expansion today. It's constant everywhere in local universe**. Expansion rate was different in the past.

Cosmological models

Modern era of cosmology started in 1917 with Einstein's paper `**Cosmological Considerations of The General Theory of Relativity**'.

In general relativity (GR), gravitation is a geometric theory and not a force. Geometry is 4-dimensional (**space-time**) and is affected by matter. Matter gives **distortion** of space-time (curvature). Newton's theory is a special case.

Curvature of space-time described by distribution of **energy and momentum**. In special relativity (special case, where gravity is ignored) matter has energy expressed by

$$E = mc^2 \qquad (5.2)$$

and photons have momentum:

$$p = E/c \qquad (5.3)$$

Distribution of energy & momentum gives space-time curvature & cosmological model.

In 3D flat space, length between 2 points is:

$$ds^2 = dx^2 + dy^2 + dz^2 \qquad (5.4)$$

(generalization of Pythagoras' theorem). Space can have curvature, negative, positive or null. In **4D geometry, time is included**:

$$ds^2 = dx^2 + dy^2 + dz^2 - c^2dt^2 \qquad (5.5)$$

Valid for flat space (special relativity). Points in 3D space are **events in 4D geometry**.

Einstein model

In this model, universe is **static and finite**. Energy and momentum homogeneous and isotropic on large scale. Curvature described by **field equations of general relativity**:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = -8\pi G/c^4 \times T_{\mu\nu} \qquad (5.6)$$

where $G_{\mu\nu}, T_{\mu\nu}$ and $g_{\mu\nu}$ are tensors, first describing **curvature of space-time**, second the **distribution of energy and momentum** (varying with time and position), third the **metric tensor used to introduce Λ**, which is cosmological constant giving **repulsive term** (negative pressure). (For $\Lambda = 0$, Eq. 5.6 explains deflection of background light by Sun.) When GR formulated (1917), expansion of the universe was not known. **Λ introduced to balance gravity and make universe stationary**. This is:

$$\Lambda = 4\pi G \rho / c^2 \qquad (5.7)$$

where ***ρ* is the cosmic density in the universe**. This is a particular value of cosmological constant, also called Λ_E. After discovery of expansion, cosmological constant defined by Einstein his "*greatest blunder*". **In Einstein model, universe is finite**. Traveling in same direction, you would reach eventually initial point after distance proportional to $1/\Lambda^{1/2}$. **This is possible if space curved positively**.

Curvature of space-time expressed by $k = -1, 0, +1$ (negative, flat and positive curvature). In **Einstein model**, curvature of space-time is positive ($k = +1$). Year after publication of Einstein model, **de Sitter** introduced different model, also with field equations, where mean mass density and pressure are zero (**effect of matter is negligible**). Geometry is given by cosmological constant and the **universe is expanding**.

Expansion regulated by **scale factor *R(t)***. In flat universe:

$$ds^2 = [R(t)]^2 (dx^2 + dy^2 + dz^2) \qquad (5.8)$$

***R(t)* defines distance between points**. In the **de Sitter model**, *R(t)* has an exponential form, where rate of expansion is proportional to cosmological constant:

$$R(t) \propto e^{Ht} \quad \text{with} \quad H = (\Lambda c^2/3)^{1/2} \qquad (5.9)$$

Consequence: if universe expanding ==> distance between objects increases with t ==> redshift. **De Sitter first introduced the concept of expansion**, later confirmed by Hubble's measurements. Λ determined by motion of galaxies.

Friedmann, Robertson and Walker (**FRW**) **models** more general and used today to express evolution of homogeneous and isotropic universe. **Einstein and de Sitter models are special cases**. Here space-time infinitesimal separation of 2 events is:

$$ds^2 = [R(t)]^2 / (1+kr^2/4)^2 (dx^2 + dy^2 + dz^2) - c^2(dt)^2 \qquad (5.10)$$

where r is distance from the origin and k the curvature. This is **Robertson-Walker metric**. In universe with pressure-free matter density ρ, $R(t)$ determined solving **Friedmann equation** (see Eq. 5.21), where ***R(t)* is related to *k*, cosmic density ρ & Λ**. It defines universe evolution and is **most important equation in cosmology**.

$R(t)$ for $\Lambda < 0$, $\Lambda = 0$, $\Lambda > 0$, $0 < \Lambda < \Lambda_E$, $\Lambda = \Lambda_E$, $\Lambda > \Lambda_E$ and k=+1,0,–1 shows expansion or contraction of homogenous & isotropic universe filled with pressure-free matter.

For $\Lambda < 0$, universe is always closed. Also for $\Lambda = 0$ $k = +1$ (maximum expansion, then contraction). R defines distance between points, not radius of universe. Only for $k = +1$ universe has finite volume and R is its radius. For $k = -1$ and 0, universe expands and contracts, but infinite. The point $R(t = 0) = 0$ is called **Big Bang**. For $\Lambda = 0$, the other point with $R(t) = 0$ is called **Big Crunch**.

Lemaître universe, with k = +1 and $\Lambda > \Lambda_E$, introduced by catholic priest G. Lemaître, who first suggested that **first nuclei formed in a hot dense face of universe** (the primeval atom or the Cosmic Egg).

Today most accredited model: ***k* = 0 and Λ > 0**. Big Bang first, then expands forever. After slowdown, expansion is now accelerated. Known as **accelerating universe**.

De Sitter model special case of accelerating universe, where $\rho = 0$. Approximation of more general universe, when it is so large that ρ is very low. Expansion is driven essentially by cosmological constant Λ at rate given by Eq. 5.9 for $t \rightarrow +\infty$.

Hubble's law and Hubble parameter

Hubble's constant defines rate of expansion of universe today:

$$H_o = 69.3 \pm 0.8 \text{ km s}^{-1} \text{ Mpc}^{-1} \qquad (5.11)$$

Distance between two points increases as universe expands. If point A emits photon when scale factor is $R(t_{em})$, that photon is seen by point B when scale factor is $R(t_{obs})$. For expansion, photon emitted at λ_{em} is stretched and gets higher wavelength when reaches B:

$$\lambda_{obs} = \lambda_{em} \times R(t_{obs}) / R(t_{em}) \qquad (5.12)$$

also expressed by redshift:

$$z = R(t_{obs}) / R(t_{em}) - 1 \qquad (5.13)$$

that is: **redshift increases with distance between galaxies**. Rate of expansion defined by FRW model. If distance between two points relatively small, then:

$$z = R(t+\Delta t) / R(t) - 1 \approx [R(t) + \Delta R(t)] / R(t) - 1 = \Delta R(t) / R(t) \qquad (5.14)$$

where:

$$\Delta R(t) = \Delta t \times \dot{R}(t) \qquad (5.15)$$

is rate of scale factor variation in short time interval *Δt* (using derivative). Then:

$$z = \Delta t \times \dot{R}(t) / R(t) = d/c \times \dot{R}(t) / R(t) \qquad (5.16)$$

where distance done by light in time interval: $d = c\Delta t$. This is similar to Hubble's law Eq. 5.1, valid for local universe. Then we define **Hubble parameter** (generalisation of Hubble constant) at time *t* as:

$$H(t) = \dot{R}(t) / R(t) \qquad (5.17)$$

At any *t*, *H(t)* represents rate of expansion (relative variation of scale factor with *t*). **This is defined by FRW model**. Hubble constant H_o is change of scale factor at time $t = t_o$ (now).

The derivative of $\dot{R}(t)$ is positive or negative, depending on whether expansion is **accelerating** or **decelerating**.

Critical density

Density of matter *ρ* important parameter of FRW model. Due to expansion or contraction, ***ρ* is time dependent***.* In local universe, ***ρ(t*** estimated by measuring mass in large volume and dividing by volume**. Generally very difficult to measure, but an estimate is possible using clusters of galaxies.

Friedmann equation gives rate of variation of scale factor in the universe:

$$\dot{R}^2(t) = 8\pi G R^2/ 3 \times [\rho + \Lambda c^2/ (8\pi G)] - kc^2 \qquad (5.21)$$

(omitted dependency from *t* for *ρ* and *R*). In **critical model, *k* = 0 and Λ = 0**, we have:

$$\dot{R}^2 = 8\pi G R^2/ 3 \times \rho_{crit} \qquad (5.22)$$

where **critical density** at *t* is:

$$\rho_{crit} (t) = 3H^2(t)/(8\pi G) \qquad (5.23)$$

which makes use of Eq. 5.17 ($H(t) = \dot{R}(t)/R(t)$). Current value of critical density for H_o is:

$$\rho_{crit}(t_o) = 3H_o^2/(8\pi G) \approx 8\times10^{-27}\ \text{kg m}^{-3} \qquad (5.24)$$

(The mass of a proton is 1.67×10^{-27} kg.) Mass density of the universe at any t expressed as a fraction of critical density:

$$\Omega_m(t) = \rho(t)/\rho_{crit}(t) \qquad (5.25)$$

If we consider the constant next to ρ in Eq. 5.21 as a density:

$$\rho_\Lambda = \Lambda c^2/(8\pi G) \qquad (5.26)$$

then we define **density parameter for the cosmological constant** as:

$$\Omega_\Lambda(t) = \rho_\Lambda/\rho_{\mathrm{crit}}(t) \qquad (5.27)$$

with $\Omega_\Lambda(t)$ time dependent. The quantity:

$$\rho_\Lambda c^2 = \Lambda c^4/(8\pi G) = u_\Lambda \qquad (5.28)$$

in units of energy per m^{-3}, is called **energy density of vacuum**. Since it **doesn't change with expansion of universe** (only constants used), expansion of universe will rather **increase the vacuum energy** when compared to other energies (radiation & matter). **Cosmological constant might be linked to vacuum energy**. It is also called **dark energy**, and is expressed also in terms of Eq. 5.27 (density parameter for dark energy).

More in general, from Friedmann equation Eq. 5.21, age of universe today depends on Λ and k, and goes up in this sequence:

1. closed model $\Lambda = 0$ & $k = +1$
2. critical model $\Lambda = 0$ & $k = 0$
3. open model $\Lambda = 0$ & $k = -1$
4. accelerating model $\Lambda > 0$ & $k = 0$

Also:

$\Omega_\mathrm{m} + \Omega_\Lambda > 1$ for $k = +1$ (closed universe) (5.29)
$\Omega_\mathrm{m} + \Omega_\Lambda = 1$ for $k = 0$ (flat universe) (5.30)
$\Omega_\mathrm{m} + \Omega_\Lambda < 1$ for $k = -1$ (open universe) (5.31)

Present matter density measurements give $\Omega_\mathrm{m} \approx 0.3$, $\Omega_\Lambda \approx 0.7$ ==> universe dominated by cosmological constant (or dark energy?), and $\Omega_\mathrm{m} + \Omega_\Lambda = 1$. Expansion of universe continues forever at accelerating rate.

Hubble time and age of the universe

Solving Friedmann Equation Eq. 5.21 for $k = 0$ and $\Lambda = 0$ (critical universe), we get:

$$R(t) \propto t^{2/3} \qquad (5.33)$$

then (from Eq. 5.17):

$$H(t) = 2/(3t) \qquad (5.34)$$

and

$$t_o = 2/(3H_o) \qquad (5.35)$$

is age of the universe. $1/H_0$ is the **Hubble time** and is 1.4×10^{10} yr. For $H_o = 70$ km/s Mpc, Eq. 5.35 gives an age of the universe for critical model $t_o = 9\times10^9$ yr, way too short. First indication that $\Lambda \neq 0$.

6. THE BIG BANG

Density of matter in universe changes with time as:

$$\rho_{\rm m} = M/V \propto 1/R^3(t) \qquad (6.1)$$

true for any cosmological model. At present time $\rho_{\rm m}(t_o) = 3\times10^{-27}$ kg m^{-3} (measured from clusters of galaxies), which is 2.6 times lower than ρ_{crit}. In the past, $\rho_{\rm m}$ was much more uniform than now. Models with **$R(t=0)=0$ foresees Big Bang where $\rho_{\rm m} = +\infty$**.

Radiation in the universe dominated by **cosmic background radiation**, which peaks at present time at microwave: $\lambda_{\rm CMB} = 1.063$ mm (then Cosmic Microwave Background - CMB). It gives a perfect black body (BB) spectrum, resulted by photons and matter in thermal equilibrium. T of BB spectrum today (from Wien's displacement law):

$$T_{CMB}(t_o) = 2.72548\pm0.00057 \text{ K} \propto 1/\lambda_{\rm CMB}(t_o) \qquad (6.2)$$

In the past, BB spectrum peaked at smaller λ:

$$\lambda_{\rm CMB}(t)/\lambda_{\rm CMB}(t_o) = R(t)/R(t_o) \qquad (6.3)$$

Therefore:

$$T_{CMB}(t) \propto 1/R(t) \qquad (6.4)$$

If universe expands with time, T higher in the past. Limit $R(t=0)=0$ in Big Bang gives infinite T (**hot Big Bang**).

There is a time when CMB is high enough to keep baryonic **matter totally ionized** (**plasma**). Opacity of gas very high, because of scattering of photons by free electrons (**Thomson scattering**, low photon energy limit of BB spectrum). **Strong interaction**

between photons and electrons (in equilibrium) ==> BB spectrum. *T* drops as universe expands, equilibrium breaks.

At present time, energy density dominated by energy density of cosmological constant ($\rho_\Lambda c^2 = u_\Lambda = 9 \times 10^{-10}$ J m^{-3}, given by Eq. 5.28) over energy density of matter ($u_{m,t_0} = \rho_{m,t_0} c^2 = 3 \times 10^{-10}$ J m^{-3}) & radiation ($u_{r,t_0} = 5 \times 10^{-14}$ J m^{-3}, given from CMB). u_Λ is energy density of **dark energy**, constant over entire history of universe, because it doesn't depend on scale factor.

Radiation energy density u_r insignificant at present time. Energy density of matter scales with volume of universe: $u_m \propto 1/R^3(t)$. For radiation, number density of photons scales same way:

$$n(t) \propto 1/R^3(t) \tag{6.5}$$

Energy of single photon is:

$$\varepsilon_{ph} = hc/\lambda \tag{6.6}$$

where $\lambda \propto R(t)$ expands with expansion of universe. Then:

$$\varepsilon_{ph} \propto 1/R(t) \tag{6.7}$$

and:

$$u_r(t) = n(t) \times \varepsilon_{ph}(t) \propto 1/R^4(t) \tag{6.8}$$

Then energy density of radiation much larger in the past, goes up faster going back in time than u_m. For $R(t)/R(t_o) < 0.1$, u_m and u_r larger than u_Λ. For **$R(t)/R(t_o) \approx 10^{-4}$ ==> $u_m \approx u_r$**. This happened when universe very young, **a few times 10^4 years old**. Before, **radiation dominated era**, universe dominated by radiation.

When energy density dominated by radiation, Friedmann equation gives **$R(t) \propto t^{1/2}$**. Since $T(t) \propto 1/R(t)$ (BB spectrum), then:

$$T \approx 1.5 \times 10^{10}\, t^{-1/2} \tag{6.9}$$

(*t* in sec and *T* in K). Then for $t = 1$ s, $T = 1.5 \times 10^{10}$ K. This is higher than *T* in core of most massive stars ==> **nuclear reactions can occur**.

Early Universe

At that time, **thermal equilibrium** between matter and radiation (same *T*). That means energy is (**interaction energy**):

$$E \sim KT \tag{6.10}$$

For $T = 10^{14}$ K, $E \approx 9$ GeV (conversion units $1\,\text{eV} = 1.60\times10^{-19}$ J).

We can understand the universe when T was lower than temperature experienced in accelerators on Earth (not more than $T < 10^{28}$ K = 10^{15} GeV ==> $t > 10^{-36}$ s). Before, theory must be used.

Standard model of quantum physics describes interactions between elementary particles. Gravity described by general theory of relativity. **Theory of everything** not found yet, when all forces are together, for $t < 10^{-43}$ s. **Planck time** (a combination of fundamental constants for all forces) is time before which all forces in a single force:

$$t_{Planck} = (Gh\,/\,2\pi c^5)^{1/2} = 5.38 \times 10^{-44}\ \text{s} \qquad (6.11)$$

Scientists believe that going back in time, 4 forces unified (gravity, electromagnetic, strong and weak). **On very small scale (large density and high temperature) strength of different forces are equal**. For $E \approx 1000$ GeV, electromagnetic and weak forces are equal (**electroweak interaction**). Weak force is responsible for both the radioactive decay and nuclear fission of subatomic particles. Important example: β decay where a proton is transformed into a neutron, or vice versa, inside an atomic nucleus. All other unifications happened for much larger T. Theory of unification of strong and electroweak is **Grand Unified Theory** (**GUT**) at $E \approx 10^{15}$ GeV, which happened for $t \sim 10^{-36}$ s. Gravitation and GUT meet for $E \approx 10^{19}$ GeV, $t \sim 10^{-43}$ s and $T \approx 10^{32}$ K (**Planck era**).

When T very high, particle-antiparticle creation (**pair-creation**). In these interactions, **conservation rules include energy, electric charge, baryon and lepton number**. Particle of mass m can be created if $E = mc^2$ is available.

At end of electroweak unification $t \sim 10^{-12}$ s and $T \approx 10^{16}$ K, and energy of photons or particles was $\boldsymbol{E = 10^3}$ **GeV (Quark Era). This is larger than rest energy of all quarks and leptons and respective antiparticles**. (Each quark has baryonic number 1/3. Leptons don't have baryonic number.)

In process of **annihilation**, particle and antiparticle involved, E released in radiation equivalent to rest energy of particles mc^2. Electron-positron annihilation means $E = 2m_ec^2 = 2 \times 0.511$ MeV = 1.02 MeV = $\boldsymbol{1.18 \times 10^{10}}$ **K**. **For this temperature or higher, electron-positron pair production takes place.**

In **Quark Era**, universe is populated by **mix of quarks, antiquarks, leptons and anti leptons** (enough E is available). Other particles are called **exchange particles**, mediating (transmitting fundamental interaction) between particles. Photon mediates electromagnetic interaction. **Gluons** mediates strong force. $\boldsymbol{W^+\ W^-\ Z^0}$ **bosons** mediate weak force.

At the time of unification of the strong and electroweak forces, the only particle expected is Higgs boson.

Dark Matter is thought to be made mostly of non-baryonic matter, nor leptons.

Inflation and end of GUT

Important event for cosmology is **Inflation** (theory, never demonstrated by observations) which probably **took place at end of GUT**, for $t \sim 10^{-36}$ s, $E \sim 10^{15}$ GeV, $T \sim 10^{28}$ K. According to theory, large number of **magnetic monopoles** would be formed in stable state, but never found by experiments today. Solution would be **inflation**: **exponential expansion** of universe, could be related to the **energy of vacuum**. Theory of inflation is solving many problems left from the Big Bang theory. The so called **false vacuum, at the end of GUT**, has a high energy density (much higher than today) and dominates.

Energy density of vacuum would drop dramatically in short time, **from $t = 10^{-36}$ s to $t = 10^{-34}$ s**. Then **transition to true vacuum**. Scale factor $R(t)$ would increase of factor 10^{50} (**inflation**). Universe gets so large that density of magnetic monopoles very low today, very hard to find.

Transition to true vacuum ==> **huge energy release and particles-antiparticles formed** (quark-antiquark, leptons-antileptons). Matter in the universe produced by inflation. Mechanism that produced inflation unknown, it solves many problems unsolved by the Big Bang.

Baryogengesis happened at the end of Inflation. Small unbalance between matter-antimatter would originate universe of baryonic matter. If it didn't exist, baryonic-dominated universe wouldn't exist (because, later, baryonic matter and antimatter would annihilate and disappear totally). This is related to violation of charge & parity symmetry (CP violation).

From $t = 10^{-34}$ s to $t = 10^{-12}$ s nothing happens ==> called **the desert**.

End of electroweak unification

$t \sim 10^{-12}$ s, $E \sim 10^{3}$ GeV, $T \sim 10^{16}$ K ==> temperature drops, **not enough creation of W^{+} W^{-} and Z^{0} bosons** (mediators of weak force) ==> electromagnetic force separates from weak force.

The quark-hadron transition

$t \sim 10^{-5}$ s, $E \sim 1$ GeV $T \sim 10^{12}$ K ==> quarks not isolated anymore form hadrons, **quark-hadron phase transition** (state of quarks in present universe) for $E \sim 200$ MeV. Many formed, **most stable hadrons that survived were neutrons and protons (and their antiparticles)**. Proton particularly stable (half-life time longer than 10^{33} years) ==> universe dominated by protons (ionized H).

Neutron is unstable, gives β^- decay:

$$n \rightarrow p + e^- + anti\text{-}\nu_e \qquad (6.12)$$

with half-life time of 880.2 ± 1.0 s, which is very stable for fast transitions in universe at that time.

For $t > 10^{-5}$ s (and it was done by $t = 10^{-2}$ s) energies low enough for **protons-antiprotons** and **neutrons-antineutrons to annihilation**. Thanks to small unbalance between particles-antiparticles that existed since GUT, baryonic universe didn't disappear. **The particle excess with respect to antiparticles derived from density of photons of CMB measured today** (for symmetry, in early universe number of baryons equal number of photons).

Today **10^9 photons present every stable baryon** (neutron or proton) ==> $1/10^9$ asymmetry between particle-antiparticle ($10^9 + 1$ particles every 10^9 antiparticles).

Protons and neutrons undergo reactions producing one another, and producing neutrinos:

$$anti\text{-}\nu_e + p \rightleftharpoons n + e^+ \qquad (6.13a)$$

$$\nu_e + n \rightleftharpoons e^- + p \qquad (6.13b)$$

When universe $t = 10^{-2}$ s, large number of neutrinos, antineutrinos, electrons and positrons available for these reactions. Neutrinos, baryons and radiation have same T (thermodynamical equilibrium).

Proton rest mass energy 938.27 MeV, smaller than that of neutron (939.56 MeV), then for T high enough (interaction energy > 1.2 MeV) ==> equal number density of neutrons n_n and protons n_p. When T drops, neutrons start to produce more protons:

$n_n / n_p \approx 0.9$ at $t \sim 10^{-2}$ s, $E = 10$ MeV
$n_n / n_p \approx 0.65$ at $t \sim 0.1$ s, $E = 3$ MeV

Neutrino decoupling and electron-positron annihilation

$t \sim 1$ s, $E \sim 1$ MeV, $T \sim 1.5 \times 10^{10}$ K.

For $t = 0.7$ s ==> reactions of Eqq. 6.13a,b happen from right to left. Neutrinos don't interact anymore ==> era named **neutrino decoupling**. **Neutrinos free to travel, don't interact ever since** ==> **cosmic neutrinos** with today $T = 1.95$ K (undetected), slightly lower than CMB, as decoupling happened before photons decoupling.

1 MeV energy required for **electron-positron pair, for lower E, e^- e^+ annihilate**:

$$e^- + e^+ \longrightarrow \gamma + \gamma \qquad (6.14)$$

Same asymmetry between e^- and e^+ of $1/10^9$ as for protons. Universe is electrically neutral. At that time, $\boldsymbol{n_n / n_p \approx 0.22}$**, which is then frozen** (no positrons available anymore for Eq. 6.13 a to happen). **The neutrons drop only for $\boldsymbol{\beta^-}$ decay**, stopped by formation of light elements.

Primordial nucleosynthesis

$t <$ few hundred seconds, $E >$ a few × 10^4 eV, $T >$ a few × 10^8 K.

For $t \sim 1$ s and $T \sim 10^{10}$ K nuclear reactions take place to form He, D and Li (**primordial nucleosynthesis**). Difference with stars is that T changed rapidly. For $T = 5 \times 10^8$ K (t = 900 s) nucleosynthesis ineffective.

First nuclear fusion between *p* and *n* gives deuterium:

$$p + n \rightleftharpoons {}^2_1\mathrm{H} + \gamma \qquad (6.15)$$

Photodisintegration of deuterium D can occur, to have reaction right-left possible in Eq. 6.15, **if $\boldsymbol{E > 2.23}$ MeV**. Although, at this time T is lower, photons many more than D, some have enough energy to destroy D. Black body (BB) spectrum of photons tells how many photons have $E > 2.23$ MeV as a function of t (every 1 baryon, 10^9 more photons). D survives when T drops even further, for $t > 3$ *minutes* and $T < 1\times10^9$ K, when fraction of photons with enough energy drops.

Other reactions take place that use *D*, to give stable nuclei ${}^4_2$He. These involve creation of tritium ${}^3_1$H and helium ${}^3_2$He.

Primordial nucleosynthesis didn't produce heavier elements because T dropped too quickly and heavier elements require more E. **Photodisintegration for higher *T* didn't allow many nuclear reactions**. Other reactions formed Li (abundance $Z < 10^{-9}$). Other **elements with mass number 5 to 8 unstable**, don't survive. Abundance of Li today important to understand physical conditions of universe at that time.

Primordial nucleosynthesis stopped for $\boldsymbol{t \sim 1000}$ s and $\boldsymbol{T \sim 5\times10^8}$ K.

When *D* forms, $\boldsymbol{n_n/n_p}$ had dropped to ≈ 0.16. In this moment, **approximately all neutrons ended up in ${}^4_2$He**. The value of Y (total mass of He over total baryonic mass) is:

$$Y = n_{He}\, m_{He} / (n_H\, m_H + n_{He}\, m_{He}) \qquad (6.16)$$

where n_H and n_{He} number density of H and He atoms. Since $m_{He} \approx 4m_H$ then:

$$Y = 4n_{He} / (n_H + 4n_{He}) \qquad (6.17)$$

We express Y in terms of n_n / n_p that existed at that time. As there are 2 neutrons in He, number of He atoms are total number of neutrons available divided by two $n_{He} = n_n / 2$, and number of H after He creation is number of protons minus 2 protons in He:

$$n_H = n_p - 2n_{He} = n_p - n_n \qquad (6.18)$$

then:

$$Y = 2n_n / (n_p + n_n) = 2 / (1 + n_p / n_n) \qquad (6.19)$$

which, **for $n_n / n_p \approx 0.16$**, gives **$Y = 0.28$**. More refined calculation gives **$Y = 0.24$**, remarkably close to interstellar value $Y = 0.24 \div 0.25$ derived in local interstellar medium. This is one of strongest predictions of hot Big Bang model. **Before, it was not understood why Y was so uniform wherever it was measured, in stars and ISM**.

At the end of primordial nucleosynthesis, elements created: D, ^3_1H (half-life 12 yr), ^3_2He, ^4_2He and Li.

Recombination and last scattering of photons

$t \sim 3 - 4 \times 10^5$ years, $E \sim$ *a few* eV, $T \sim 4500$ to 3000 K.

When primordial nucleosynthesis stops, light elements present together with electrons, neutrinos, photons and non-baryonic dark matter. **Electrons, photons and nuclei in thermal equilibrium, have same T**.

Thermal equilibrium stopped when **T continued to drop faster for photons than electrons, and interactions between photons and electrons become negligible**.

H ionized, if photons with energy above 13.6 eV abundant, or collisional ionization important. As photons still 10^9 more than protons, **one every 10^9 with energy larger than 13.6 eV would keep H ionized**.

For further expansion and drop of temperature, protons combine with electrons to form neutral H. Process called **recombination**, **starts for $T = 4500$ K**, $t = 3 \times 10^5$ yr after Big Bang. **By $T = 3000$ K, free electron so rare, that scattering of photons by electrons rare event**. Cosmic Microwave Background (CMB) we detect today is relic of **last scattering of photons by electrons**. Universe becomes **transparent to radiation**.

As $T(t) \propto 1/R(t)$, redshift of last scattering is (Eq. 5.13):

$$z = R(t_o) / R(t_{last}) - 1 = T(t_{last}) / T(t_o) - 1 = 3000/2.725 - 1 \approx 1100 \qquad (6.22)$$

Surface of the universe at distance $z = 1100$ in every direction all around us is called **last scattering surface**.

Before recombination, **radiation pressure prevents gravitational collapse of overdense regions**. **After recombination, gravitational instabilities start to grow.**

The cosmic microwave radiation (CMB)

Discovered in 1965 by A. Penzias & R. Wilson, initially detected at $\lambda = 7.35$ cm. It's perfect BB spectrum (most perfect ever detected) gives today $T = 2.72548 \pm 0.00057$ K ($\lambda_{max} = 1.063$ mm) and very uniform all over the sky. Important source of information about origin of the universe. First important mission to measure CMB was COBE, then WMAP, the last is *Planck,* launched in 2009.

Large uniformity of T_{CMB} at surface of last scattering not easy to understand. In fact, under conditions of uniform expansions, regions in last scattering surface separated by more than **2 degrees in the sky would have not be connected** (limit of light speed), uniform T not expected. Problem known as **horizon problem**, solved by inflation.

Anisotropies of CMB

COBE measured that one direction of sky T is 3.36 mK higher than mean value, and opposite direction is 3.36 mK lower than mean value (**dipole anisotropy**). Due to motion of Earth (around the Sun, Sun around Galaxy, Galaxy peculiar motion, motions of local group) with respect to cosmic background photons.

Direction of the sky where blue-shift of BB spectrum is highest represents direction of motion of Earth with respect to Hubble flow (due to universe expansion). **This gives 365 km s^{-1}. Motion of Local Group with respect to Hubble flow is 630 km s^{-1}.**

Once dipole anisotropy removed, still anisotropy present on smaller scale, a few parts over 10^5, due to **primordial fluctuations** of density in early universe, which occurred during inflation ($t \sim 10^{-36}$ s). Very important cosmological probe, these small fluctuations helpful to understand gravitational collapse.

CMB photons traveling from surface of last scattering also affected by gravity close to high-mass objects. These anisotropies give information on space-time geometry.

Formation of first structures in the universe

Large uniformity of CMB tells that also matter density was very uniform at $z \sim 1100$. However, universe today highly non uniform (galaxies and clusters of galaxies formed).

In early universe, primordial fluctuations of matter density very small, $\boldsymbol{\Delta\rho/\rho \sim 10^{-5}}$ (as suggest by CMB anisotropies). **Overdense region feels two opposite effects: gravity contracts matter, while pressure stabilizes it**.

Before recombination, pressure is provided by photons and electrons. **At recombination, electron pressure drops** (electrons bound to atoms) and radiation pressure negligible. Thermal pressure of gas fighting alone against gravity, much smaller than radiation pressure before recombination. Jeans mass drops from $M_J = 10^{16}$ M$_\odot$ to $M_J = 10^5$ M$_\odot$. **Fluctuations with mass 10^5 M$_\odot$ first to virialize (gravitationally bound systems).** This is the mass of globular clusters today.

Detailed calculations of Jeans mass, for the case of baryonic mass only, give $\Delta T/T \sim 10^{-3}$ for CMB fluctuations, much larger than measured. Problem solved by presence of dark matter. In particular, **cold dark matter** (**CDM**) doesn't interact with baryons and doesn't feel recombination, then density fluctuations can grow before recombination.

Computer simulations of structure formation in the universe **rule out a universe with $\Omega_m = 1$ and $\Lambda = 0$. Most accepted models of the universe today are ΛCDM models, that is with $\Lambda \neq 0$ and cold (non relativistic) dark matter**.

7. GLOSSARY:

AGN: Active Galactic Nucleus
BB: Black Body
BH: Black Hole
BLR: Broad Line Region
CDM: Cold Dark Matter
CMB: Cosmic Microwave Radiation
DM: Dark Matter
FIR: Far Infrared
FRW: Friedmann, Robertson and Walker
GC: Globular Cluster
GR: General Relativity
HDM: Hot Dark Matter
HR: Hertzsprung-Russell
HST: Hubble Space Telescope
IGM: Intergalactic Medium
IR: Infrared
ICM: Intracluster Medium
IR: infrared
ISM: Interstellar Medium
LMC: Large Magellanic Cloud
MW: Milky Way
NLR: Narrow Line Region
NIR: Near Infrared
QSO: Quasi Stellar Object, also known as quasar
Quasar: Quasi-Stellar Radio Source
SED: Spectral Energy Distribution

SF: Star Formation
SFR: Star Formation Rate
Sgr: Sagittarius
SMC: Small Magellanic Cloud
SN: supernova